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(54) MULTI-PASS FRICTION STIR WELDING

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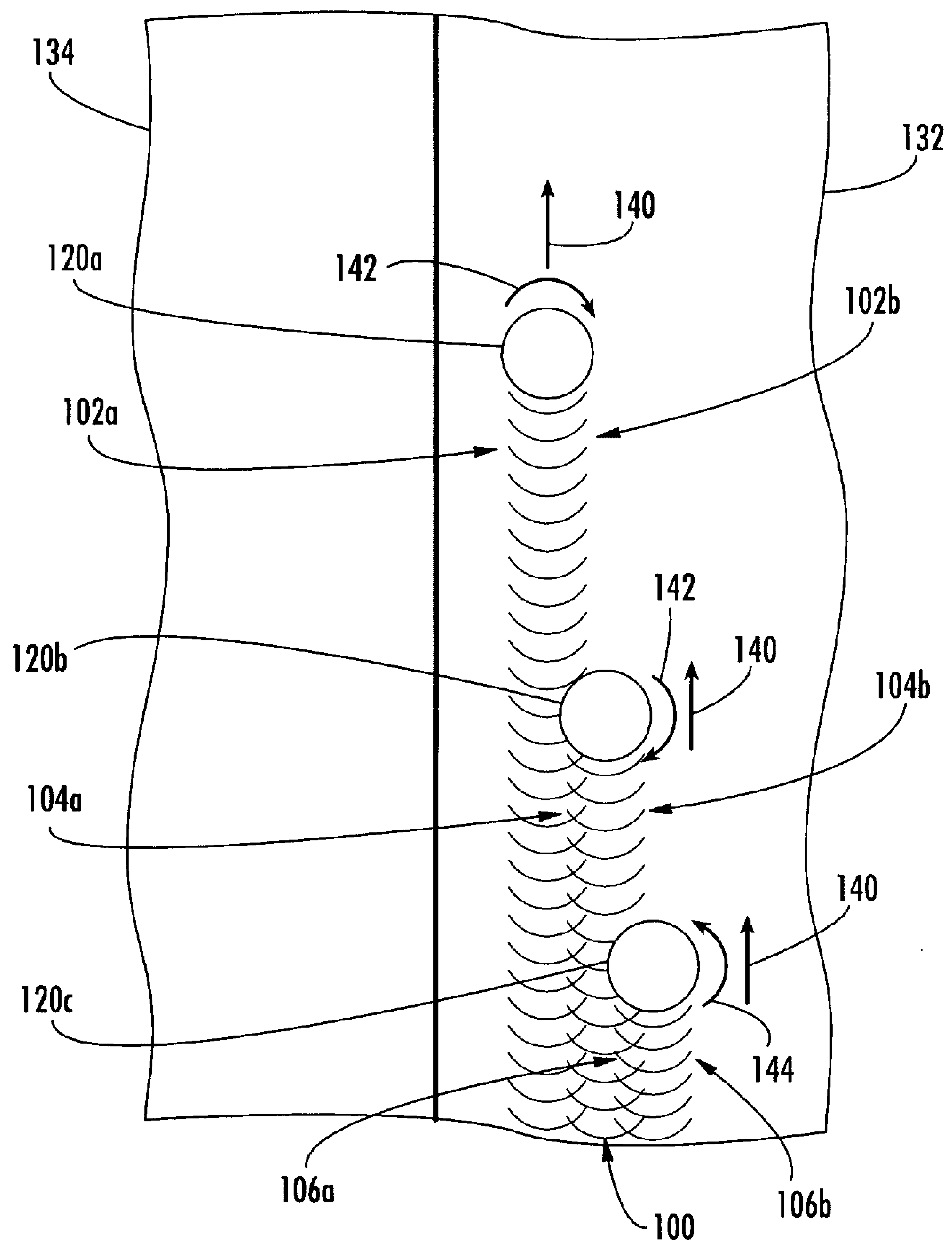
(57) ABSTRACT

A multi-pass friction stir weld joint and method for forming such joints are provided. The multi-pass weld joint is formed of at least first-pass and second-pass friction stir weld joints that are disposed in the workpiece in a substantially parallel configuration. The first- and second-pass joints define transversely opposite advancing and retreating sides, and the second-pass joint is disposed to at least partially overlap the retreating side of the first-pass joint. Thus, at least some of the material of the workpiece in the first-pass joint is processed during the formation of the second-pass joint.



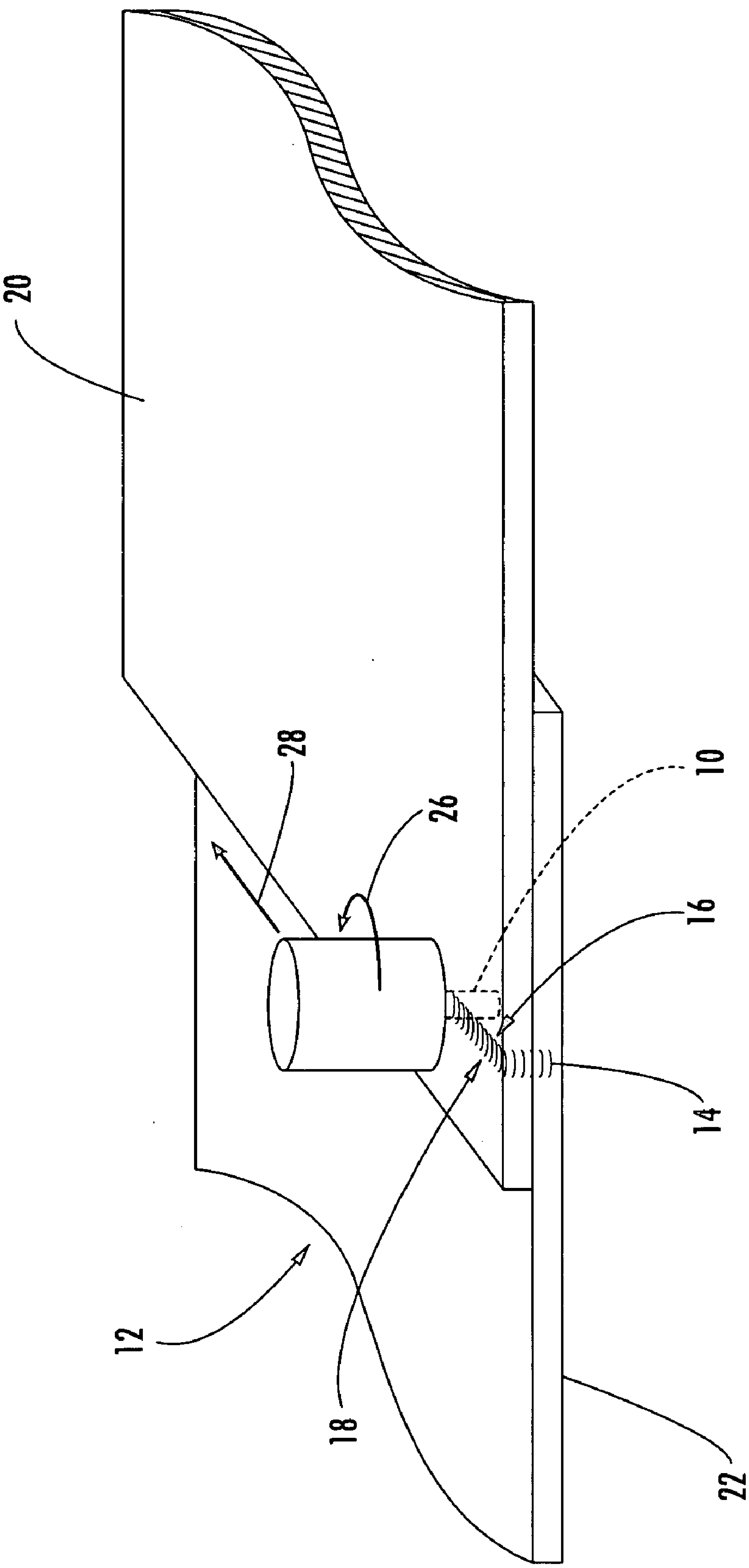



FIG. 1
(PRIOR ART)

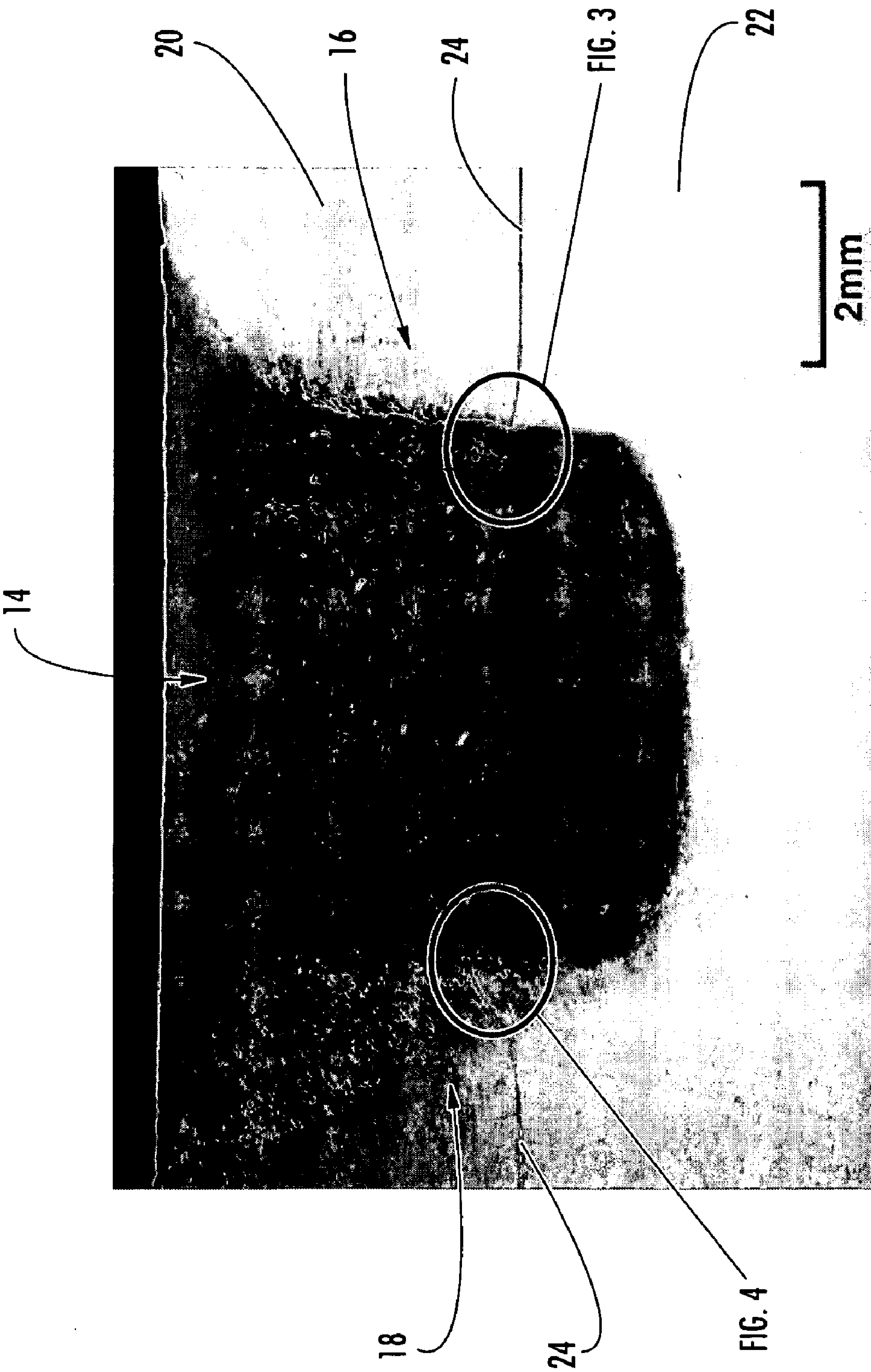



FIG. 2
(PRIOR ART)

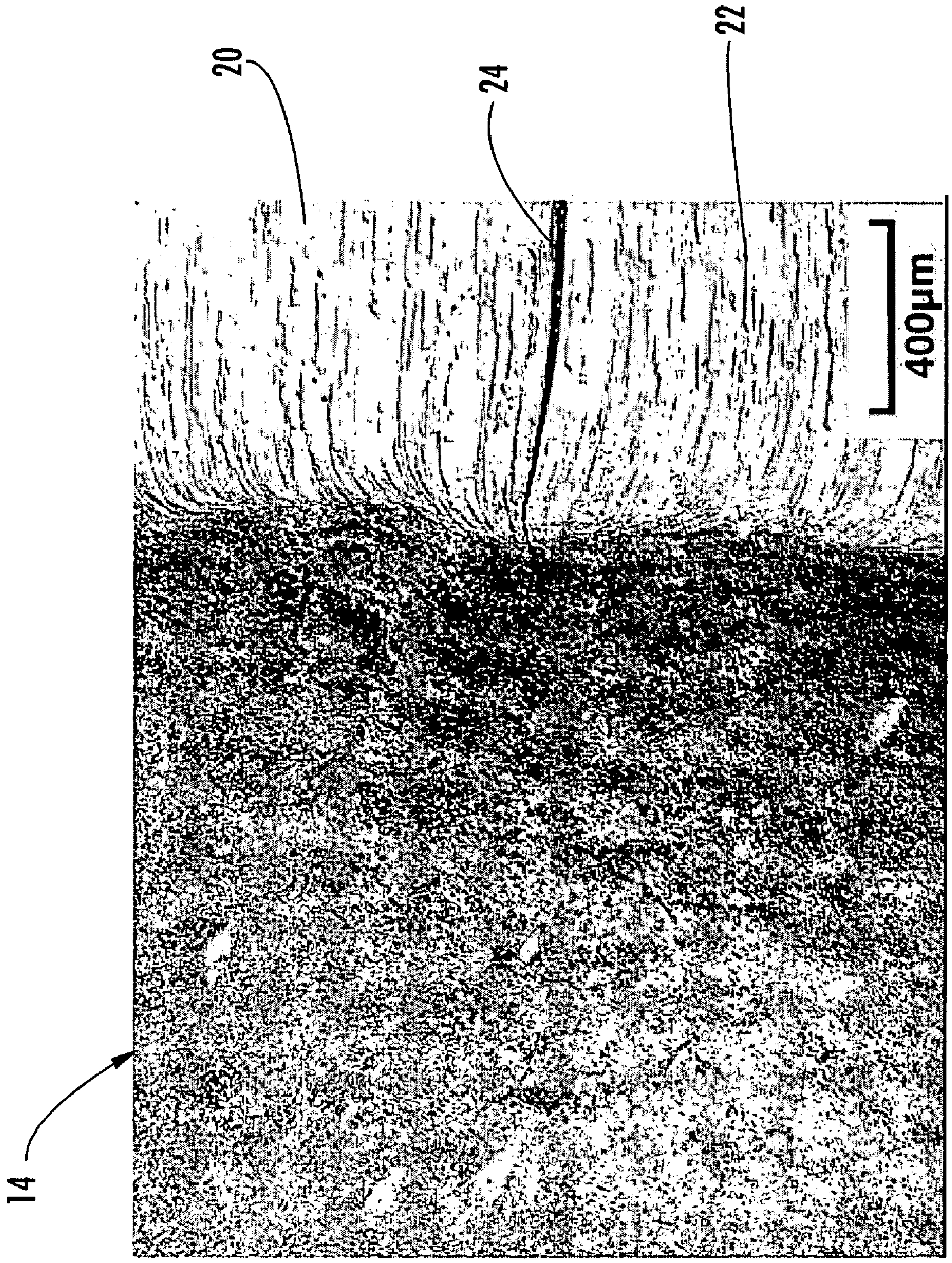



FIG. 3
(PRIOR ART)

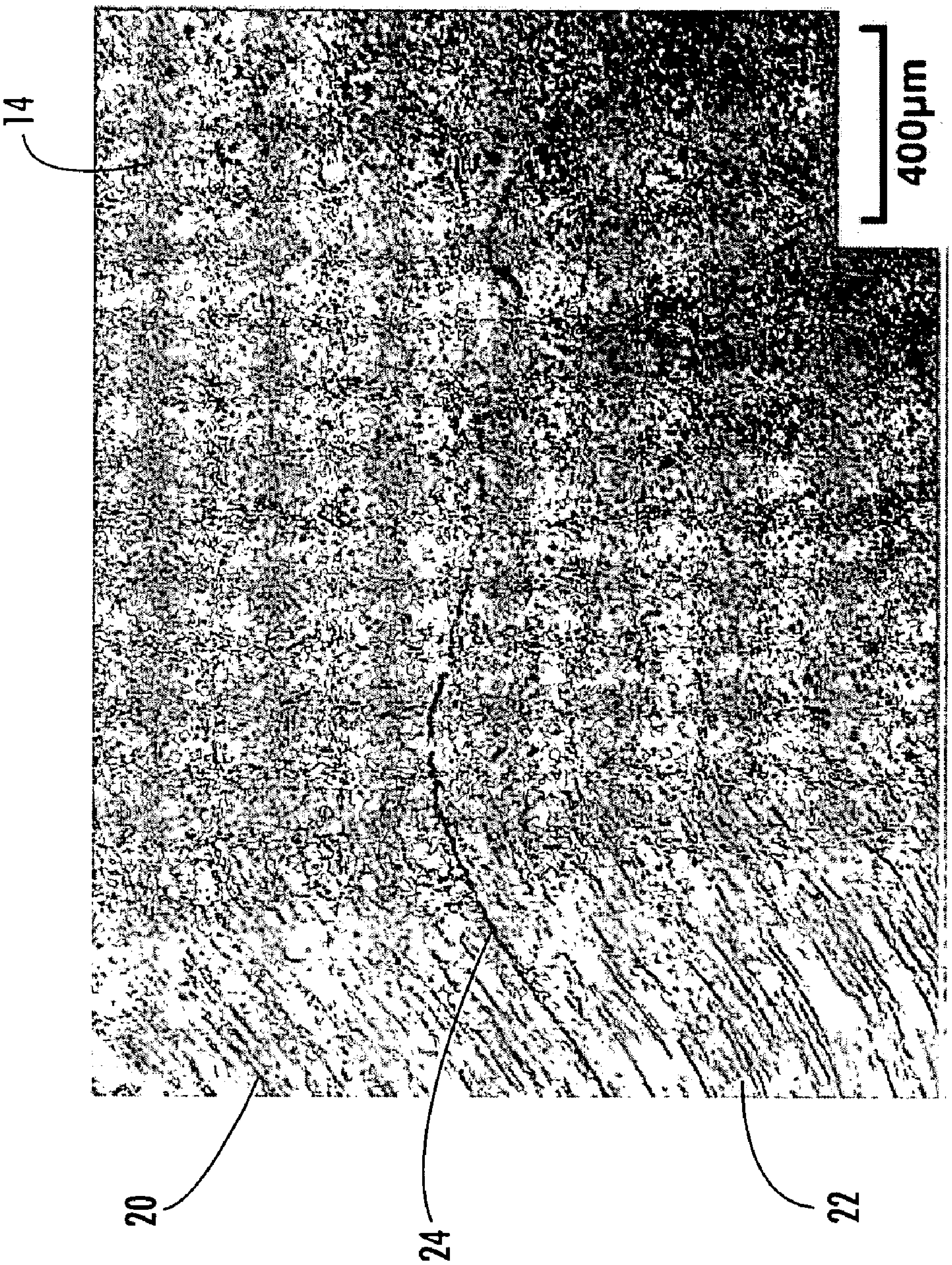



FIG. 4
(PRIOR ART)

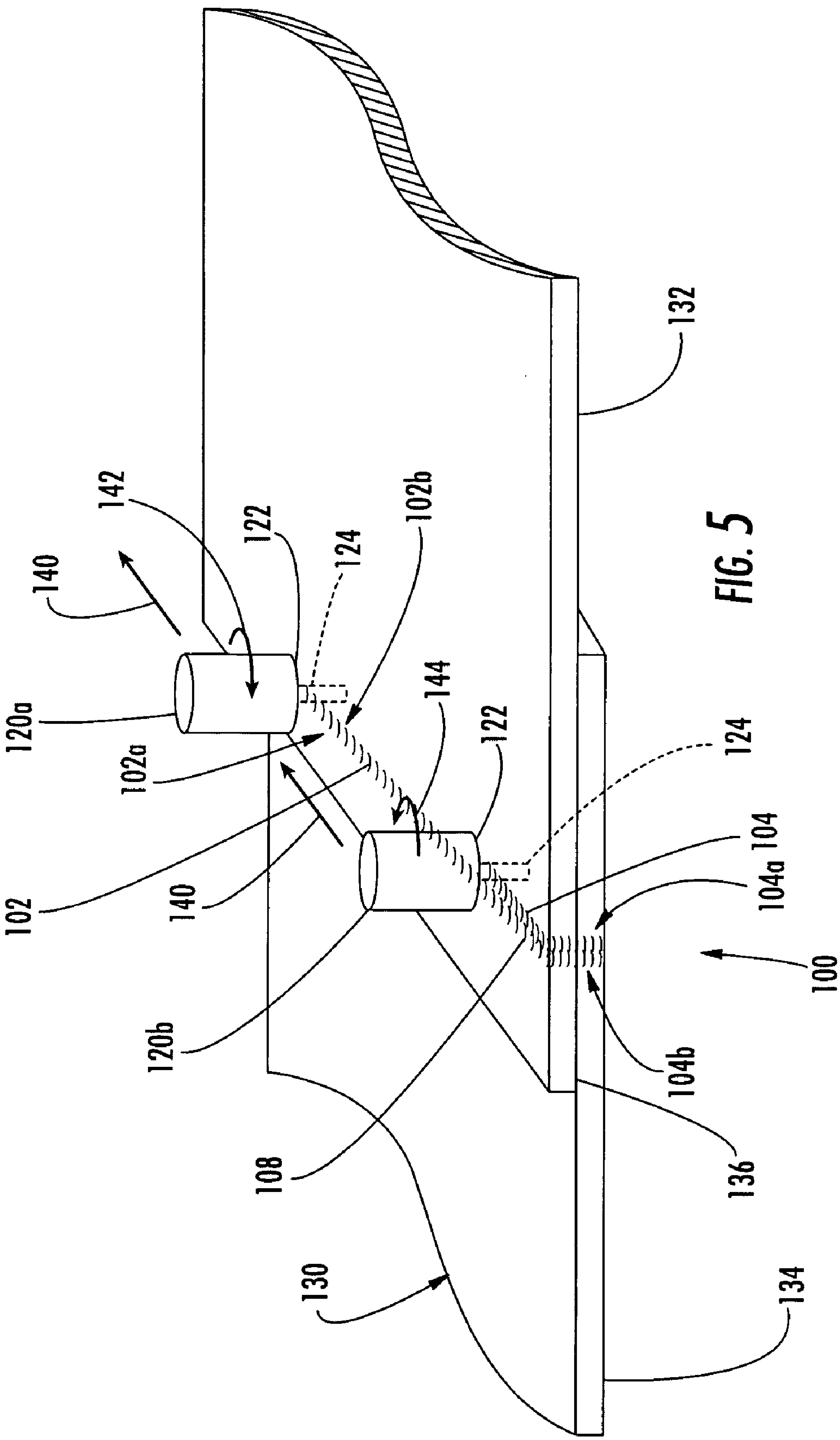

132
142
140
122
124
102b
120a
102a
102
140
144
122
124
104
104a
100
120b
104b
108
136
130
134

FIG. 5

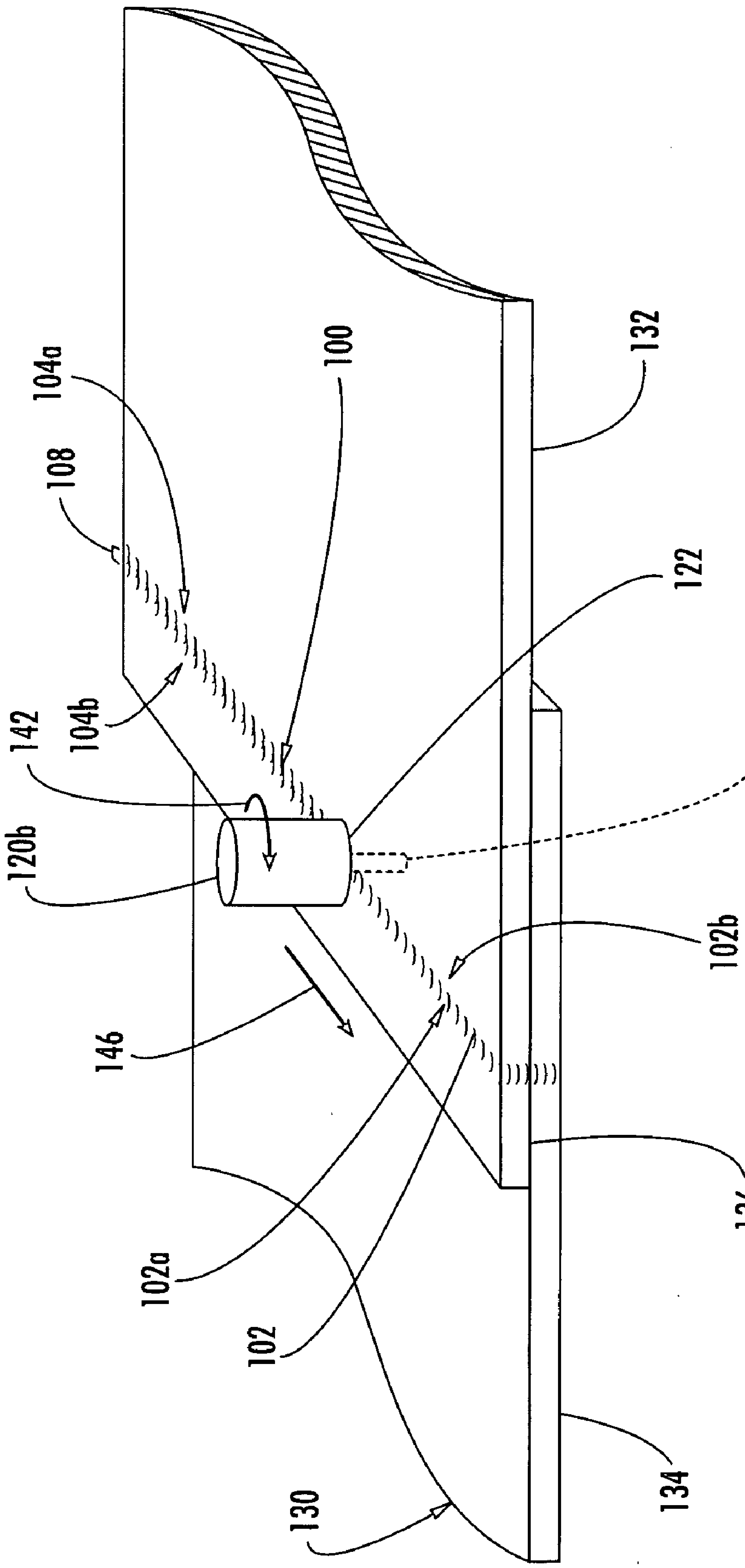

104a
108
100
132
122
142
104b
124
120b
102b
146
136
102a
102
134
130

FIG. 6

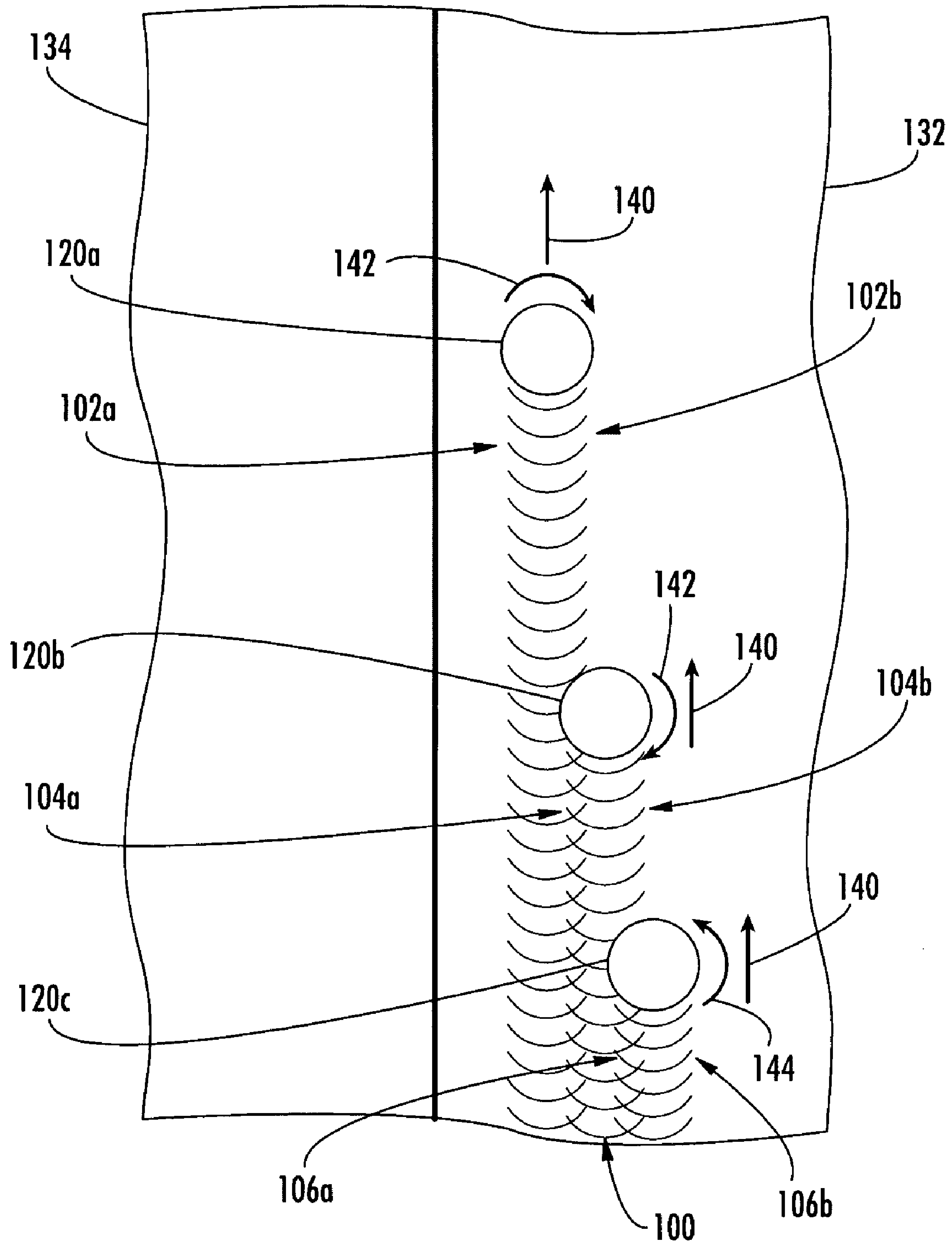

134
132
140
142
120a
102b
102a
142
140
120b
104b
104a
140
120c
144
106a
100
106b

FIG. 7

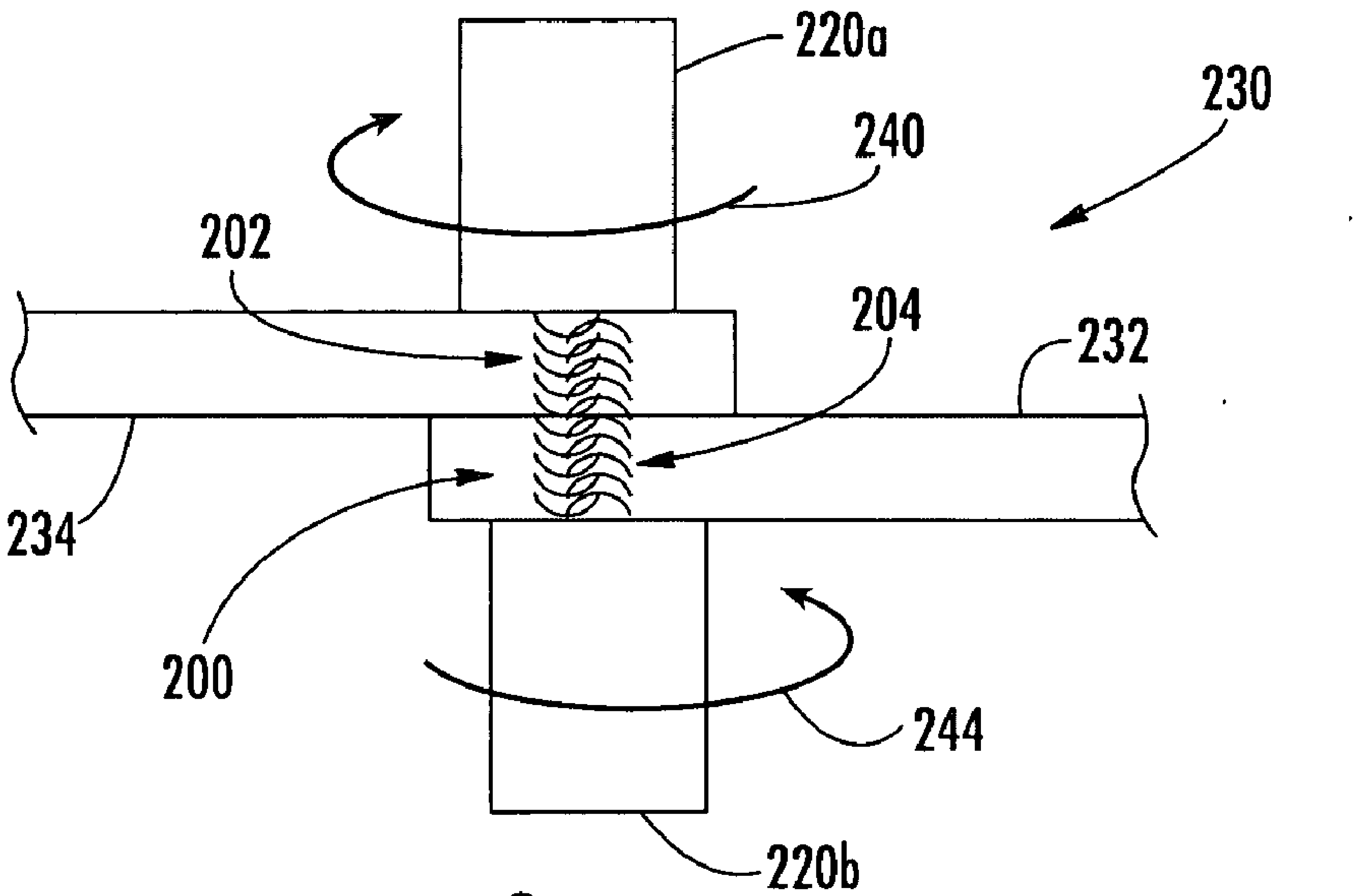

220a
230
240
202
204
232
234
200
244
220b

FIG. 8

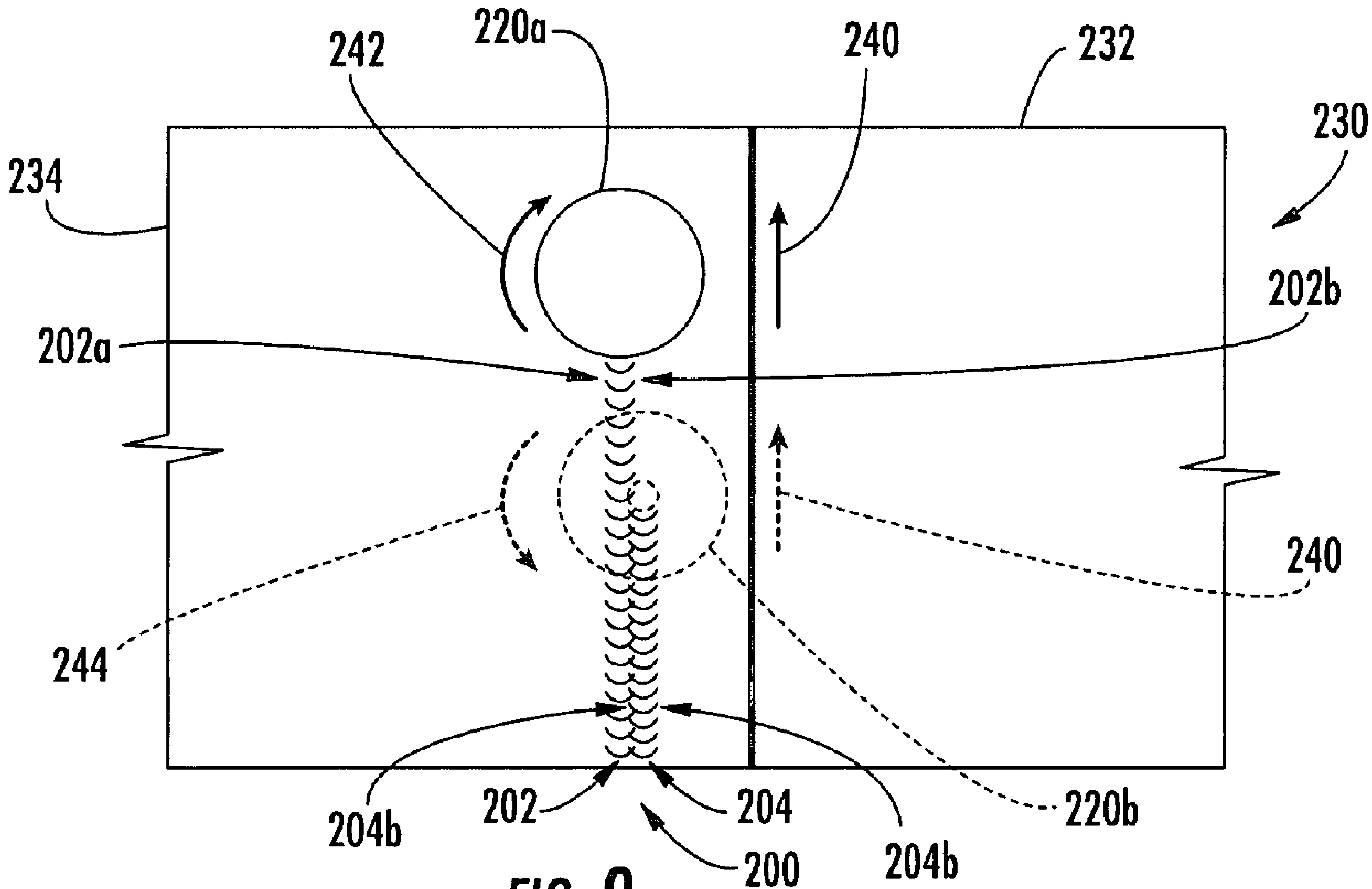

242
220a
240
232
230
234
202a
202b
240
244
204b
202
204
200
204b
220b

FIG. 9

# MULTI-PASS FRICTION STIR WELDING

## BACKGROUND OF THE INVENTION

[0001] 1) Field of the Invention

[0002] The present invention relates to friction welding and, more specifically, to a method for overlapping friction stir weld joints to form multi-pass friction stir weld joints.

[0003] 2) Description of Related Art

[0004] Friction stir welding is a process in which a rotating tool, such as a pin or probe, is urged into and/or through a workpiece, e.g., to join multiple members of the workpiece in a solid state or to repair cracks in a workpiece. Typically, the pin extends from a shoulder, which can be flat, concave, or otherwise contoured, and the shoulder is urged against the workpiece so that the pin is urged therein. The pin is then urged through the workpiece to form a continuous weld joint. For example, during one conventional friction stir welding process, a friction stir welding machine urges the probe of the rotating tool into an interface defined by two abutting workpiece members, and moves the tool along the interface. The motion of the rotating tool generates frictional heating, thereby forming a region of plasticized material in the workpiece. The tool can be tilted approximately 2.5° relative to the workpiece such that the trailing edge of the shoulder is thrust into and consolidates the plasticized material. Upon solidification of the plasticized material, the members of the workpiece are joined along the weld joint. Friction stir welding is further described in U.S. Pat. No. 5,460,317 to Thomas et al., the contents of which are incorporated herein by reference.

[0005] Friction stir weld joints are typically not uniform throughout due, at least in part, to the asymmetry of the conventional friction stir welding process. In particular, a conventional friction stir weld joint is characterized by transversely opposite advancing and retreating sides. As shown in **FIG. 1**, a friction stir weld pin **10** is rotated and advanced longitudinally through a workpiece **12**, i.e., two overlapping structural members **20**, **22**, to form a friction stir weld lap joint **14**. The pin **10** is rotated in a direction **26** and advanced longitudinally in a direction **28**. The relative speed of the outer surface of the pin **10** with respect to the workpiece **12** is a function of the rotational speed of the pin **10** and the speed of the longitudinal advancement of the pin **10** through the workpiece **12**. In particular, the speed of the pin **10** relative to the workpiece **12** at a first side **16**, referred to as the advancing side, is generally equal to the sum of the speed of the longitudinal movement of the pin **10** and the product of the rotational, or angular, speed of the pin **10** and the radius of the pin **10**. Similarly, the speed of the pin **10** relative to the workpiece **12** at the second side **18**, referred to as the retreating side, is generally equal to the product of the rotational speed of the pin **10** and the radius of the pin **10** less the speed of the longitudinal movement of the pin **10**. Thus, the relative speed is greater at the advancing, first side **16** of the joint **14**, and slower at the retreating, second side of the joint **18**.

[0006] The material of the workpiece **12** at the advancing side **16** of the joint **14** is typically displaced more and mixed more thoroughly than the material at the retreating side **18** of the joint **14**. **FIG. 2** illustrates a lap weld joint **14** formed between two anodized aluminum structural members **20**, **22**, with the friction stir welding pin **10** rotating at 625 revolutions per minute and advanced longitudinally at a speed of 7.5 inches per minute. **FIGS. 3 and 4** illustrate portions at the advancing and retreating sides **16**, **18**, respectively, of the joint **14**. The material at the advancing side **16** exhibits better dispersion as compared to the material at the retreating side **18**. In particular, the interface **24** between the anodized surfaces of the structural members **20**, **22** is still evident, albeit deformed, at the retreating side **18**. In contrast, the material at the advancing side **16** is mixed so that the interface **24** no longer exists. The incomplete mixing of the material at the retreating side **18** of the joint **14** can reduce the strength of the joint **14**, especially where the interface **24** of the structural members **20**, **22** extends from the joint **14**, as is the case in a friction stir welded lap joint.

[0007] Thus, conventional friction stir welding methods have been shown to form weld joints in which the material of the workpiece is plasticized and mixed, and the resulting granular structure in the weld joint is refined. However, a need continues to exist for an improved friction stir weld joint in which the material has been sufficiently mixed and refined throughout and for an improved method for forming such joints. Preferably, the method should be capable of forming a lap joint, in which the joint extends substantially perpendicular through the interface.

## SUMMARY OF THE INVENTION

[0008] The present invention provides a multi-pass friction stir weld joint and a method for forming such joints in a workpiece. The multi-pass friction stir weld joint is formed of first-pass and second-pass friction stir weld joints that are at least partially disposed in the workpiece in a substantially parallel configuration. Each of the first- and second-pass joints defines transversely opposite advancing and retreating sides, and the second-pass friction stir weld joint at least partially overlaps the retreating side of the first-pass friction stir weld joint. Thus, material at the retreating side of the first-pass joint that may be insufficiently mixed during formation of the first-pass joint is re-mixed during the formation of the second-pass joint.

[0009] According to one embodiment of the present invention, the advancing sides of the first- and second-pass friction stir weld joints are disposed transversely opposite so that the retreating side of the second-pass friction stir weld joint at least partially overlaps the first-pass friction stir weld joint. Further, the retreating side of the second-pass friction stir weld joint can be disposed substantially entirely within the first-pass friction stir weld joint. The second-pass joint can overlap at least about two-thirds, or at least about nine-tenths, of a width of the first-pass joint.

[0010] According to one aspect of the invention, a third-pass friction stir weld joint is also disposed in the workpiece. The third-pass friction stir weld joint extends substantially parallel to the first-pass joint and at least partially overlaps the retreating side of the second-pass joint so that the three joints in combination form the multi-pass friction stir weld joint.

[0011] The workpiece can include at least two structural members defining an interface therebetween, and the first- and second-pass joints can extend through the interface to define a lap joint between the structural members. The workpiece can be formed of materials such as aluminum, aluminum alloys, titanium, titanium alloys, and steel.

[0012] The present invention also provides a method of friction stir welding a workpiece. The method includes rotating a friction stir welding pin and urging the friction stir welding pin in a first direction against the workpiece to plasticize a portion of the workpiece and form the first-pass joint therein. The same friction stir welding pin, or a different pin, is then rotated and urged against the workpiece to plasticize a portion of the workpiece and form the second-pass joint so that the second-pass joint at least partially overlaps the retreating side of the first-pass joint. For example, the first- and second-pass joints can be formed by urging the friction stir welding pin in the same direction and rotating the pin in opposite rotational directions. Alternatively, the joints can be formed by urging the pin in opposite directions and rotating the pin in the same direction. First and second pins can be used for forming the respective first- and second-pass joints, and the pins can have dissimilar contours on their outer surfaces, e.g., to define opposite orientations that can be rotated in opposite directions.

[0013] The overlap portion of the first- and second-pass joints can vary, and can be determined according to a desired width of the resulting multi-pass joint and a width of each of the first- and second-pass joints. Further, a third-pass joint can at least partially overlap the retreating side of the second-pass joint.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The foregoing and other advantages and features of the invention, and the manner in which the same are accomplished, will become more readily apparent upon consideration of the following detailed description of the invention taken in conjunction with the accompanying drawings, which illustrate preferred and exemplary embodiments, but which are not necessarily drawn to scale, wherein:

[0015] **FIG. 1** is a perspective view illustrating a conventional friction stir welding tool used for forming a friction stir weld lap joint between two structural members;

[0016] **FIG. 2** is a section view of a conventional friction stir weld lap joint;

[0017] **FIG. 3** is a partial section view of the conventional friction stir weld joint of **FIG. 2**, showing a portion of the joint at the advancing side of the joint as indicated in **FIG. 2**;

[0018] **FIG. 4** is a partial section view of the conventional friction stir weld joint of **FIG. 2**, showing a portion of the joint at the retreating side of the joint as indicated in **FIG. 2**;

[0019] **FIG. 5** is a perspective view illustrating a multi-pass friction stir weld joint during formation according to one embodiment of the present invention;

[0020] **FIG. 6** is a perspective view illustrating a multi-pass friction stir weld joint during formation according to another embodiment of the present invention;

[0021] **FIG. 7** is a plan view illustrating a multi-pass friction stir weld joint during formation according to yet another embodiment of the present invention;

[0022] **FIG. 8** is an elevation view illustrating a multi-pass friction stir welding joint during formation according to a still another embodiment of the present invention; and

[0023] **FIG. 9** is a plan view illustrating the multi-pass friction stir welding joint of **FIG. 8**.

## DETAILED DESCRIPTION OF THE INVENTION

[0024] The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

[0025] Referring now to the drawings and, in particular, to **FIG. 5**, there is shown a multi-pass friction stir weld joint **100** in a workpiece **130** during formation according to one embodiment of the present invention. The multi-pass joint **100** is formed of first-pass and second-pass friction stir weld joints **102**, **104**, which at least partially overlap.

[0026] The first- and second-pass friction stir weld joints **102**, **104** can be formed using friction stir welding tools **120*a***, **120*b***, each of which includes a rotatable shoulder **122**, a pin **124** extending therefrom, and at least one actuator (not shown) for rotating the respective tool **120*a***, **120*b*** and moving the tool **120*a***, **120*b*** longitudinally through the workpiece **130**. The shoulder **122** and pin **124** of each tool **120*a***, **120*b*** can be engaged to a chuck, spindle, or other member that is engaged to the actuator, which can be any of various types of actuating devices, including electric, hydraulic, or pneumatic devices. For example, the actuator can be part of a machine, such as a milling machine or a drill, that is structured for rotating and moving the friction stir welding tool **120*a***, **120*b***. The actuator be operated manually, but preferably is operated by a computer, microprocessor, microcontroller or other controller, which can be programmed to operate according to a schedule such as a schedule stored in or created by a computer software program.

[0027] The pin **124** and shoulder **122** are preferably formed of a material having high strength and heat resistance. For purposes of example only and not limitation, the pin **124** and/or shoulder **122** can be constructed of tool steel, a molybdenum alloy, such as TZM, nickel alloys, such as Rene **41** (UNS N07041), and iron-nickel alloys. The shoulder **122** is structured to be urged against the workpiece **130** so that the pin **124** is inserted into the workpiece **130**, e.g., into a lap interface **136** as shown in **FIG. 5**. In other embodiments of the invention, the tool **120*a***, **120*b*** can include a second shoulder that is structured to oppose the first shoulder **122** with the pin **124** extending therebetween so that the shoulders can be disposed opposite the workpiece **130** and frictionally engaged to opposite surfaces of the workpiece **130** while the pin **124** extends through the workpiece **130**. In either case, each shoulder **122** of the tools **120*a***, **120*b*** can define a surface that is generally flat, tapered, concave, convex, or otherwise shaped, e.g., to engage the workpiece **130** and prevent "plowing," in which plasticized material from the workpiece **130** is pushed radially outside the circumference of the shoulder **122** as the tool **120***a*, **120***b* is moved along the workpiece **130**. Further, each shoulder **122** can define one or more frictional features, e.g., raised portions or surfaces such as threads, bumps, or ribs that are structured to frictionally engage the workpiece **130**. For example, a spiral thread can be provided on the shoulder **122** to engage the workpiece **130**. The pin **124** defines a stirring portion that engages the workpiece **130** during welding, and the stirring portion of the pin **124** can be cylindrical or can define a variety of shapes and contours including helical threads, circumferential grooves, ridges, tapers, steps, and the like.

[**0028**] The urging force of the shoulder **122** against the workpiece **130** can be opposed by an anvil or other support device (not shown) positioned opposite the shoulder **122** or by a second shoulder connected to the pin **124** and positioned opposite the workpiece **130**. Thus, the workpiece **130** can be "sandwiched" between the shoulder **122** and the additional shoulder or support device during friction stir welding. Advantageously, the shoulder **122** and the second shoulder or other support device can create a seal that prevents the plasticized material from being extruded therefrom. Thus, planar or otherwise desired contours can be formed on the opposing sides of the workpiece **130** at the weld joint **100**. The rotating friction stir welding tool **120***a*, **120***b* can be moved through the workpiece **130** along a predetermined path to thereby form the elongate weld joints **102, 104**. Thus, the material of the workpiece **130** can be mixed by the pin **124**, and the grain size of the material can be refined, thereby improving the material properties of the material at the joint **100**.

[**0029**] Two friction stir welding tools **120***a*, **120***b* are illustrated in **FIG. 5** for purposes of illustrative clarity, but the first- and second-pass friction stir weld joints **102, 104** can alternatively be formed using a single friction stir weld tool **120***a*, **120***b* that is moved longitudinally through the workpiece **130** in successive passes. Thus, the term "pass" refers to the motion of the friction stir weld tool **120***a*, **120***b* through the workpiece **130**, and successive passes can be performed by a single tool **120***a*, **120***b* at different times or by different tools **120***a*, **120***b* at the same or different times. Each pass, while defining a generally longitudinal direction, need not be linear. In fact, the joints **102, 104** and, hence, the multi-pass joint **100**, can be formed in any desired configuration in the workpiece **130**. In addition, the joints **102, 104** can extend from an edge of the workpiece **130**, i.e., by configuring the tool **120***a*, **120***b* at an edge of the workpiece **130**, rotating the pin **124**, and urging the tool **120***a*, **120***b* against and through the workpiece **130**. Thus, the shoulder **122** contacts the surface of the workpiece **130**, thereby constraining the axial movement of the plasticized material of the workpiece **130**, and the pin **122** plasticizes and mixes the material of the workpiece **130**. Alternatively, each weld joint **102, 104** can begin or end at a point inward from the edge of the workpiece **130**, e.g., by urging, or "plunging," the pin **124** into the workpiece **130** at the start of the weld joint **102, 104** and/or subsequently retracting the pin **124** therefrom after welding.

[**0030**] Further, the tools **120***a*, **120***b* used during the multiple passes can be the same or different. For example, some conventional friction stir welding tools have pins **124** that define features such as helical threads that are structured to be rotated in a particular direction. Rotation of such pins **124** in the opposite direction can be ineffective for friction stir welding. Thus, if successive passes of a multi-pass friction stir weld joint **100** are to be performed by rotating the tools **120***a*, **120***b* in opposite directions, different pins **124** can be provided for the successive passes. The pins **124** and/or shoulders **122** of the tools **120***a*, **120***b* can be similar except for a reverse orientation of the features. Alternatively, the pins **124** and/or shoulders **122** can differ in other respects, e.g., diametrical size, length, number or configuration of features, and the like.

[**0031**] The term "workpiece" is not meant to be limiting, and it is understood that the workpiece **130** can include one or more structural members **132, 134**, which can be configured in various configurations. Preferably, at least two structural members **132, 134** are positioned in an overlapping configuration to define the interface **136** therebetween that can be welded to form the joint **100**, i.e., a lap weld joint formed by configuring the pin **124** to extend through the interface **136** as shown in **FIG. 5**. Alternatively, other types of joints can similarly be formed. For example, a butt joint can be formed by abutting the edge surfaces of the structural members **132, 134** and welding through an interface **136** of the abutting surfaces with the pin **124** substantially parallel to the interface **136**. The structural members **132, 134** can also be positioned and welded in other configurations, and any number of structural members **132, 134** can be joined by the joint **100**. In another embodiment, the workpiece **130** can include a single structural member and the friction stir weld joint can be formed in the single member, e.g., to join overlapping portions of the member, to repair a crack, hole, or other defect therein, or to affect the material properties of the structural member.

[**0032**] The structural members **132, 134** can be formed of a variety of materials including, but not limited to, aluminum, aluminum alloys, titanium, titanium alloys, steel, and the like. Non-metal materials can also be welded according to the present invention, e.g., materials such as polymers and the like. Further, the workpiece **130** can include members of similar or dissimilar materials, for example, structural members formed of different metals, including metals that are unweldable or uneconomical to join by conventional fusion welding techniques. Unweldable materials, when joined by conventional fusion welding techniques, produce relatively weak weld joints that tend to crack during weld solidification. Such materials include aluminum and some aluminum alloys, particularly AA series **2000** and **7000** alloys. The use of friction stir welding permits workpieces formed of unweldable materials to be securely joined. Friction stir welding also can be used to securely join weldable materials to other weldable and to unweldable materials. Thus, the materials that form the workpiece **130** can be chosen from a wider variety of light weight, high strength metals and alloys, thereby facilitating reduction of the overall weight of the workpiece **130** and a structural assembly formed therefrom.

[**0033**] The workpiece **130** formed according to the methods of the present invention can be used in a variety of applications, including, for example, frames, panels, skins, airfoils, and the like for aeronautical and aerospace structures such as aircraft and spacecraft, for marine vehicles, automobiles, and the like, as well as for other applications outside of the transportation industry. The friction stir weld joints **100** can be used for joining large workpieces and workpieces having curvilinear geometries. In some applications, the members **132**, **134** are joined in geometrical configurations that make difficult, or prevent, access to the opposing sides of the workpiece **130**. For example, the structural members **132**, **134** can be joined to form a partially or fully closed body such as a tube or an airplane wing.

[**0034**] Each of the first- and second-pass weld joints **102**, **104** defines first and second transversely opposite sides and, more particularly, advancing sides **102***a*, **104***a* and retreating sides **102***b*, **104***b*. The advancing side **102***a*, **104***a* of each joint **102**, **104** is characterized during forming by a generally greater speed of the outer surface of the pin **124** and the shoulder **122** relative to the workpiece **130** than the relative speed of the outer surface of the pin **124** and the shoulder **122** at the transversely opposite retreating side **102***b*, **104***b*. That is, as the tool **120***a*, **120***b* is rotated and the pin **124** is moved longitudinally through the workpiece **130**, the relative speed of the outer surface of the pin **124** and the shoulder **122** with respect to the workpiece **130** is a function of the rotational speed of the tool **120***a*, **120***b* and the speed of the longitudinal advancement of the tool **120***a*, **120***b* through the workpiece **130**. The difference in relative speeds at the advancing and retreating sides **102***a*, **104***a*, **102***b*, **104***b* is typically determined by the direction of rotation of the tool **120***a*, **120***b* and the direction of longitudinal movement of the tool **120***a*, **120***b* through the workpiece **130**. Thus, the speed of the pin **124** relative to the workpiece **130** at the advancing side **102***a*, **104***a* is generally equal to the sum of the speed of the longitudinal movement of the pin **124** and the product of the rotational, or angular, speed of the pin **124** and the radius of the pin **124**. Similarly, the speed of the pin **124** relative to the workpiece **130** at the retreating side **102***b*, **104***b* is generally equal to the product of the rotational speed of the pin **124** and the radius of the pin **124** less the speed of the longitudinal movement of the pin **124**. Thus, the relative speed is greater at the advancing side **102***a*, **104***a* of the joint **100** and slower at the retreating side **102***b*, **104***b* of each joint **100**.

[**0035**] As shown in **FIG. 5**, the second-pass friction stir weld joint **104** is formed substantially parallel to and at least partially overlapping the first-pass friction stir weld joint **102**. While the entire second-pass friction stir weld joint **104** is shown to be substantially parallel to the first-pass friction stir weld joint **102**, it is appreciated that the second-pass friction stir weld joint **104** can alternatively be only partially substantially parallel thereto. That is, a portion of the second-pass friction stir weld joint **104** can be substantially parallel to the first-pass friction stir weld joint **102**, and other portion(s) of the second-pass friction stir weld joint **104** can be non-parallel to the first-pass friction stir weld joint **102**. Preferably, the second-pass friction stir weld joint **104** overlaps the retreating side **102***b* of the first-pass friction stir weld joint **102** so that the material at the retreating side **102***b* of the first-pass friction stir weld joint **102** is mixed again during formation of the second-pass friction stir weld joint **104**. Thus, if the material at the retreating side **102***b* of the first-pass friction stir weld joint **102** is not sufficiently mixed during the first pass, the second-pass of the friction stir weld tool **120***b* for forming the second-pass friction stir weld joint **104** can enhance the mixing of the material. By enhancing the mixing of the material of the workpiece **130**, a sufficient amount of dispersion can be achieved throughout the joint **100**, such that the joint **100** is free of weak portions and generally exhibits a sufficiently refined granular structure throughout.

[**0036**] The second-pass friction stir weld joint **104** can be formed such that the retreating side **104***b* thereof is disposed at least partially overlapping the first-pass friction stir weld joint **102**. Thus, the friction stir weld joints **102**, **104** can be formed with the advancing sides **102***a*, **104***a* transversely opposite and the retreating sides **102***b*, **104***b* overlapped. For example, as shown in **FIG. 5**, the first-pass friction stir weld joint **102** can be formed by urging and moving the friction stir welding pin **124** of the first tool **120***a* in a first direction **140** and rotating the pin **124** in a first rotational direction **142**. Subsequently, the second-pass friction stir weld joint **104** can be formed by urging and moving the pin **124** of the second tool **120***b* in the same direction **140**, while rotating the pin **124** in an opposite direction **144**. Alternatively, as shown in **FIG. 6**, the first-pass friction stir weld joint **102** can be formed as described above, and the second-pass friction stir weld joint **104** can be formed by urging and moving the pin **124** of the second tool **120***b* in an opposite direction **146**, while rotating the pin **124** in the same direction **142** as the direction of rotation while forming the first-pass friction stir weld joint **102**. In either case, the retreating side **102***b* of the first-pass friction stir weld joint **102** can be substantially overlapped by the second-pass friction stir weld joint **104**, and the retreating side **104***b* of the second-pass friction stir weld joint **104** can be disposed substantially entirely within the first-pass friction stir weld joint **102**.

[**0037**] The amount of overlap of the two friction stir weld joints **102**, **104** can vary according to such factors as the amount of mixing achieved throughout the width of each joint **102**, **104** during each friction stir welding operation, the desired amount of total mixing throughout the width of the multi-pass joint **100**, the positional accuracy of the welding device, and the like. For example, the overlap of the two friction stir weld joints **102**, **104** can be increased to compensate for a reduced amount of mixing of the individual single-pass joints **102**, **104**, and/or the overlap can be increased to achieve an increased amount of total mixing throughout the width of the multi-pass joint **100**. In addition, an overlapped portion **108** of the first weld joint **102** can be maintained at a maximum, e.g., about nine-tenths of the width of the first weld joint **102**, to ensure that the retreating side **104***b* of the second-pass friction stir weld joint **104** does not extend outward from the advancing side **102***a* of the first-pass friction stir weld joint **102**, and thereby possibly introduce areas of insufficient mixing outside the area of the first-pass friction stir weld joint **102**. For one typical single-pass friction stir weld joint, about one-third of the joint closest to the advancing side is generally sufficiently mixed, about one-third of the joint closest to the retreating side is generally insufficiently mixed, and the area therebetween may be sufficiently mixed. Thus, according to one embodiment of the present invention, the second-pass friction stir weld joint **104** is disposed to overlap at least about two-thirds of the width of the first-pass friction stir weld joint **102**. In addition, the width of the overlap portion **108**, i.e., the amount of overlapping of the two joints **102**, **104**, can be determined according to the desired width of the finished multi-pass friction stir weld joint **100**. For example, the width of the overlap **108** can be equal to about the sum of the respective widths of the two joints **102**, **104**, less the desired width of the multi-pass joint **100**.

[**0038**] It is also appreciated that the multi-pass friction stir weld joint **100** can be formed of any number of single-pass joints **102**, **104**. Thus, the multi-pass joint **100** can define any desired width. Advantageously, each single pass joint **102**, **104** can be narrower than the width of the multi-pass joint **100** and, therefore, can be formed using a pin **124** and/or shoulder **122** having a diameter smaller than that which would be required to form a weld joint of equal width in a single pass. Further, the forging and lateral forces required for moving a narrow pin through a workpiece (and for moving a narrow shoulder in contact with the workpiece) is generally less than that required for moving a wider pin (and a wider shoulder). Therefore, the single-pass joints **102**, **104** can be formed with less force than otherwise required to form a friction stir weld joint of similar width to the multi-pass joint **100**, and the single-pass joints **102**, **104** can be formed more quickly and/or with an actuator or machine having a reduced capacity to urge the pin **124** through the workpiece **130** with the shoulder **122** in contact with the workpiece **130**.

[**0039**] For example, as illustrated in **FIG. 7**, the multi-pass friction stir weld joint **100** includes first-, second-, and third-pass friction stir weld joints **102**, **104**, **106**. Preferably, the retreating side **102***b* of the first-pass joint **102** is at least partially overlapped by the second-pass or third-pass joints **104**, **106**. Further, the retreating side **104***b* of the second-pass joint **104** can be overlapped by the third-pass joint **106**, and a retreating side **106***b* of the third-pass joint **106** can be disposed within one of the first- and second-pass joints **102**, **104** so that the material at the retreating sides **102***b*, **104***b*, **106***b* of each of the joints **102**, **104**, **106** is mixed at least twice during the formation of the multi-pass joint **100**. For example, as illustrated in **FIG. 7**, the first- and second-pass joints **102**, **104** can be formed by rotating the friction stir welding tools **120***a*, **120***b* in the same rotational direction **142** and urging the tools **120***a*, **120***b* in the same longitudinal direction **140**, such that the advancing side **104***a* of the second-pass joint **104** at least partially overlaps the retreating side **102***b* of the first-pass joint **102**. The third-pass joint **106** can then be formed by rotating a friction stir welding tool **120***c* in the opposite direction **144** and urging the tool **120***c* in the same longitudinal direction **140**, such that the retreating side **106***b* of the third-pass joint **106** at least partially overlaps the retreating side **104***b* of the second-pass joint **104**. Alternatively, the third-pass joint **106** could be formed by rotating the friction stir welding tool **120***c* in the same direction and urging the tool **120***c* in a direction opposite to the direction **140** of the first and second passes so that the retreating side **106***b* of the third-pass joint **106** at least partially overlaps the retreating side **104***b* of the second-pass joint **104**.

[**0040**] Further, according to other embodiments of the present invention, the retreating and advancing sides of single-pass joints can define transversely opposite sides of the joint **100**. For example, as shown in **FIG. 7**, the advancing side **102***a* of the first-pass joint **102** is disposed transversely opposite to the retreating side **104***b* of the second-pass joint **104**. The first- and second-pass joints **102**, **104** can form a connection between the structural members **132**, **134** without the third-pass joint **106**. Additional single-pass joints can also be formed between the structural members **132**, **134**, with each successive single-pass joint having the same orientation as the first- and second-pass joints **102**, **104** such that the resulting multi-pass joint **100** defines transversely opposite retreating and advancing sides.

[**0041**] It is also appreciated that each pass of the friction stir weld joints can be formed from either side of the workpiece. For example, **FIGS. 8 and 9** illustrate a multi-pass friction stir weld joint **200** connecting first and second structural members **232**, **234** of a workpiece **230**. The multi-pass weld joint **200** includes first- and second-pass friction stir weld joints **202**, **204**. First and second friction stir welding tools **220***a*, **220***b*, each of which can be similar to the tools described above, are configured to form the joints **202**, **204** from opposite sides of the workpiece **230**. In particular, the first friction stir welding tool **220***a* is configured to be rotated in a first rotational direction **242** and urged in a longitudinal direction **240** of the joint **200**. Thus, the first-pass friction stir weld joint **202** has transverse advancing and retreating sides **202***a*, **202***b*, as shown. The second friction stir welding tool **220***b* is configured to be rotated in a second rotational direction **244** and urged in the longitudinal direction **240** of the joint **200**. Thus, the second-pass friction stir weld joint **204** has transverse advancing and retreating sides **204***a*, **204***b*, as shown. The second-pass friction stir weld joint **204** is substantially parallel to the first-friction stir weld joint **202** and partially overlaps the first-pass friction stir weld joint **202**. Although two friction stir weld tools **220***a*, **220***b* are shown in **FIGS. 8 and 9**, it is understood that the different single pass joints **202**, **204** of the friction weld joint **200** can be formed using a single tool. Further, any number of passes can be overlapped to form the multi-pass friction stir welding joint **200**, and the single pass joints can be disposed in any order.

[**0042**] Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed is:

**1**. A method of friction stir welding a workpiece, the method comprising:

rotating a friction stir welding pin and urging the friction stir welding pin in a first direction against the workpiece to thereby plasticize a portion of the workpiece and form a first-pass friction stir weld joint therein defining an advancing side and a retreating side; and

rotating the friction stir welding pin and urging the friction stir welding pin against the workpiece to thereby plasticize a portion of the workpiece and form a second-pass friction stir weld joint therein at least partially substantially parallel to the first-pass friction stir weld joint, the second-pass friction stir weld joint defining an advancing side and a retreating side,

wherein the second-pass friction stir weld joint at least partially overlaps the retreating side of the first-pass friction stir weld joint such that the first-pass and second-pass friction stir weld joints form a multi-pass friction stir weld joint.

2. A method according to claim 1 wherein said second rotating step comprises urging the friction stir welding pin in the first direction and wherein said first and second rotating steps comprise rotating the pin in opposite rotational directions.

3. A method according to claim 1 wherein said second rotating step comprises urging the friction stir welding pin in a second direction opposite the first direction and wherein said first and second rotating steps comprise rotating the pin in a same rotational direction.

4. A method according to claim 1 wherein said second rotating step comprises disposing the retreating side of the second-pass friction stir weld joint substantially entirely within the first-pass friction stir weld joint.

5. A method according to claim 1 further comprising rotating the friction stir welding pin and urging the friction stir welding pin against the workpiece to thereby plasticize a portion of the workpiece and form a third-pass friction stir weld joint therein, the third-pass friction stir weld joint being substantially parallel to the first-pass friction stir weld joint and defining an advancing side and a retreating side, and the third-pass friction stir weld joint at least partially overlapping the retreating side of the second-pass friction stir weld joint such that the first-pass, second-pass, and third-pass friction stir weld joints form the multi-pass friction stir weld joint.

6. A method according to claim 1 wherein said second rotating step comprises overlapping an overlap portion of the first-pass friction stir weld joint with the second-pass friction stir weld joint, the first-pass friction stir weld joint defining a width in a transverse direction extending between the advancing and retreating sides and the overlap portion of the first-pass friction stir weld joint being at least about two-thirds the width of the first-pass friction stir weld joint.

7. A method according to claim 6 wherein said second rotating step comprises overlapping at least about nine-tenths of the width of the first-pass friction stir weld joint.

8. A method according to claim 1 further comprising determining a width of an overlap portion of the of the first-pass friction stir weld joint according to a desired width of the multi-pass friction stir weld joint and a width of the first-pass and second-pass friction stir weld joints and wherein said second rotating step comprises overlapping the overlap portion of the first pass friction stir weld joint with the second-pass friction stir weld joint.

9. A method according to claim 1 further comprising positioning at least two structural members to form the workpiece defining an interface between the structural members, and wherein said first and second rotating steps comprise configuring the pin to extend in a direction substantially perpendicular to the interface, thereby forming a lap joint between the structural members.

10. A method according to claim 1 further comprising providing a first friction stir welding pin before said first rotating step and replacing the first friction stir welding pin with a second friction stir welding pin between said first and second rotating steps, the first and second friction stir welding pins defining dissimilar contours on outer surfaces thereof.

11. A method according to claim 1 wherein said rotating steps comprise urging the pin into the workpiece in substantially opposite directions from opposite sides of the workpiece.

12. A method according to claim 1 further comprising providing the workpiece, the workpiece comprising at least one of the group consisting of aluminum, aluminum alloys, titanium, titanium alloys, and steel.

13. A method of friction stir welding a workpiece, the method comprising:

positioning at least two structural members to form the workpiece defining an interface between the structural members;

rotating a friction stir welding pin, configuring the pin to extend in a direction substantially perpendicular to the interface between the structural members, and urging the friction stir welding pin in a first direction against the workpiece to thereby plasticize a portion of the workpiece and form a first-pass friction stir weld joint therein defining an advancing side and a retreating side; and

rotating the friction stir welding pin, configuring the pin to extend in a direction substantially perpendicular to the interface between the structural members, and urging the friction stir welding pin against the workpiece to thereby plasticize a portion of the workpiece and form a second-pass friction stir weld joint therein at least partially substantially parallel to the first-pass friction stir weld joint, the second-pass friction stir weld joint defining an advancing side and a retreating side,

wherein the second-pass friction stir weld joint at least partially overlaps the retreating side of the first-pass friction stir weld joint such that the advancing side of the second-pass friction stir weld joint is disposed transversely opposite the first-pass friction stir weld joint, and the retreating side of the second-pass friction stir weld joint being substantially entirely disposed within the first-pass friction stir weld joint, the first-pass and second-pass friction stir weld joints thereby forming a multi-pass friction stir weld lap joint between the structural members.

14. A method according to claim 13 wherein said second rotating step comprises overlapping an overlap portion of the first-pass friction stir weld joint with the second-pass friction stir weld joint, the first-pass friction stir weld joint defining a width in a transverse direction extending between the advancing and retreating sides and the overlap portion of the first-pass friction stir weld joint being at least about two-thirds the width of the first-pass friction stir weld joint.

15. A method according to claim 14 wherein said second rotating step comprises overlapping at least about nine-tenths of the width of the first-pass friction stir weld joint.

16. A method according to claim 14 wherein said first and second rotating steps comprise urging the pin into the workpiece in substantially opposite directions from opposite sides of the workpiece.

17. A multi-pass friction stir weld joint disposed in a workpiece including at least one structural member, the friction stir weld joint comprising:

a first-pass friction stir weld joint disposed in the workpiece, the first-pass friction stir weld joint extending longitudinally and defining transversely opposite advancing and retreating sides; and

a second-pass friction stir weld joint disposed in the workpiece and defining transversely opposite advancing and retreating sides, the second-pass friction stir weld joint extending substantially parallel to the first-pass friction stir weld joint and at least partially overlapping the retreating side of the first-pass friction stir weld joint such that the first-pass and second-pass friction stir weld joints form the multi-pass friction stir weld joint.

**18**. A multi-pass friction stir weld joint according to claim 17 wherein the advancing side of the second-pass friction stir weld joint is disposed transversely opposite the first-pass friction stir weld joint such that the retreating side of the second-pass friction stir weld joint at least partially overlaps the first-pass friction stir weld joint.

**19**. A multi-pass friction stir weld joint according to claim 17 wherein the retreating side of the second-pass friction stir weld joint is disposed substantially entirely within the first-pass friction stir weld joint.

**20**. A multi-pass friction stir weld joint according to claim 17 further comprising a third-pass friction stir weld joint disposed in the workpiece and defining transversely opposite advancing and retreating sides, the third-pass friction stir weld joint extending substantially parallel to the first-pass friction stir weld joint and at least partially overlapping the retreating side of the second-pass friction stir weld joint such that the first-pass, second-pass, and third-pass friction stir weld joints form the multi-pass friction stir weld joint.

**21**. A multi-pass friction stir weld joint according to claim 17 wherein the second-pass friction stir weld joint overlaps an overlap portion of the first-pass friction stir weld joint, the overlap portion being at least about two-thirds of a width of the first-pass friction stir weld joint in a transverse direction extending between the advancing and retreating sides.

**22**. A multi-pass friction stir weld joint according to claim 17 wherein the second-pass friction stir weld joint overlaps an overlap portion of the first-pass friction stir weld joint, the overlap portion being at least about nine-tenths of a width of the first-pass friction stir weld joint in a transverse direction extending between the advancing and retreating sides.

**23**. A multi-pass friction stir weld joint according to claim 17 wherein the workpiece includes at least two structural members defining an interface therebetween, the first-pass and second-pass friction stir weld joints extending through the interface to define a lap joint between the structural members.

**24**. A multi-pass friction stir weld joint according to claim 17 wherein the workpiece comprises at least one of the group consisting of aluminum, aluminum alloys, titanium, titanium alloys, and steel.

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